EQL Report No. 20

AGGREGATE WATER AVAILABILITY FOR ENERGY DEVELOPMENT IN THE UPPER COLORADO RIVER BASIN

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ABSTRACT

Can a large (significant in national terms) energy-recovery industry be developed in the Upper Colorado River Basin (UCRB), alongside more traditional water uses, without causing a problem in the aggregate quantity of water supplied to the Lower Colorado River Basin? This report answers that question in a "reasonably conservative" manner by slightly overpredicting demand and underpredicting supply.

First, aggregate consumption of water in the UCRB due to water-intensive energy industries is calculated as a function of the level of energy production. Reasonably conservative (i.e., on the high side) estimates of unit water requirements for coal-electric generation, coal-slurry pipelines, coal gasification (to produce substitute natural gas — SNG), and oil-shale processing are developed from an extensive literature survey. These are combined with various energy-development scenarios, also developed from a literature survey, to give total energy-related water consumption as a function of total energy industry size. Overall total UCRB water consumption can then be found by adding to the energy-related water use all non-energy-related consumption.

On the supply side, aggregate UCRB water availability is determined from the results of a steady-state, stochastic hydrologic model which predicts the reliability of flow to the lower basin as a function of total UCRB consumption. Predictions of the model are conservative, in the sense of being on the low side, because: (1) the period of record used to determine tributary flows is a relatively low flow period and (2) because the use of excess stored water above

steady-state levels during transition periods to steady state is ignored.

Demand and supply are then presented together in a graphical form which allows the reader to determine for him-or-herself the level of energy development which can be allowed in the UCRB, depending on the levels he or she chooses for non-energy-related water consumption in the upper basin and the reliability of water supply to the lower basin. On an <u>aggregate</u> basis, there appears to be enough water available in the Upper Colorado River Basin to produce about 7 quads per year (7×10^{15} Btu/yr or 7.4×10^{18} J/yr, equivalent to well over one-half current liquid fuel imports) from the region's fossil fuel resources by water-intensive energy industries and still allow an increase in other water uses by more than 25% (about 0.8 million acre-feet per year($9.8 \times 10^8 m^3$/yr)) over what they now are.

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LIST OF UNITS AND ABBREVIATIONS

acre-ft	acre-foot (1 acre-ft = 3.26×10^5 gal = 1.23×10^3 m^3)
acre-ft/Btu	acre-foot per British thermal unit (1 acre-ft/Btu = 1.17 m^3/J)
acre-ft/yr	acre-foot per year (1 acre-ft/yr = 1.23×10^3 m^3/yr)
bbl	barrel, U.S. (oil) (1 bbl = 4.20×10^1 gal = 1.59×10^{-1} m^3)
bpd	barrel per day (1 bpd = 1.59×10^{-1} m^3/d)
bpdOE	barrel per day oil equivalent (heating value ≃ 6.0×10^6 Btu)
Btu	British thermal unit (1 Btu = 1.055×10^3 J)
CONAES	Committee on Nuclear and Alternative Energy Systems(see Ref 2)
d	day (1 day = 1.44×10^3 min)
ft	foot (1 ft = 3.048×10^{-1} m)
gal	gallon, U.S. (1 gal = 8.35 lb H_2O at 50°F = 3.79×10^{-3} m^3)
J	joule
kg	kilogram
m	meter
MW or MW(e)	megawatt (electric) (1 MW = 3.6×10^9 J/hour)
quad	quadrillion Btu (1 quad = 1.00×10^{15} Btu = 1.055×10^{18} J)
scf	standard cubic foot (1 scf = 2.83×10^{-2} m^3)
scfd	standard cubic foot per day (1 scfd = 2.83×10^{-2} m^3/d)
SNG	Substitute (synthetic, high-Btu) natural gas (heating value ≃ 960 Btu/scf)
t	ton, U.S. (short) (1 ton = 9.07×10^2 kg)
UCRB	Upper Colorado River Basin
WPA	Water Purification Associates, Inc., Cambridge, MA.
yr	year (1 yr = 3.65×10^2 day - at 100% stream factor)

CHAPTER 1

INTRODUCTION

Water will be needed in order to develop the fossil fuel resources of the Upper Colorado River Basin. Because of the semi-arid character of the region this water consumption may severely limit the extent of the energy-resource development. How severe a limit it will be, and for what reasons, are very complex issues and have been the subjects of much controversy. The approach taken in this paper is to try to find a definitive answer to only one of the simpler, yet still important water supply questions: can a large (significant in national terms) energy recovery industry be developed in the Upper Colorado River Basin, alongside more traditional water uses, without causing a problem in the aggregate quantity of water supplied to the Lower Colorado River Basin? The answer arrived at below is yes, even allowing for significant increases over current levels in uses by other economic sectors, though possibly less than their currently unused appropriations.

1.1 Background

The fossil energy resources of the Upper Colorado River Basin are quite extensive, see Figures 1.1 and 1.2. The total coal reserve base of the upper basin (proven reserves minable at a profit under current market conditions) is approximately 24.5 billion tons (2.22×10^{13} kg, Reference 1). Of this, about 20% is strippable coal. Approximately 45% of all the coal, and 60% of the strippable coal, is low sulfur coal (less than 1% by weight). By way of comparison, total current U.S. coal production for all 48 contiguous states is about 0.6 billion tons

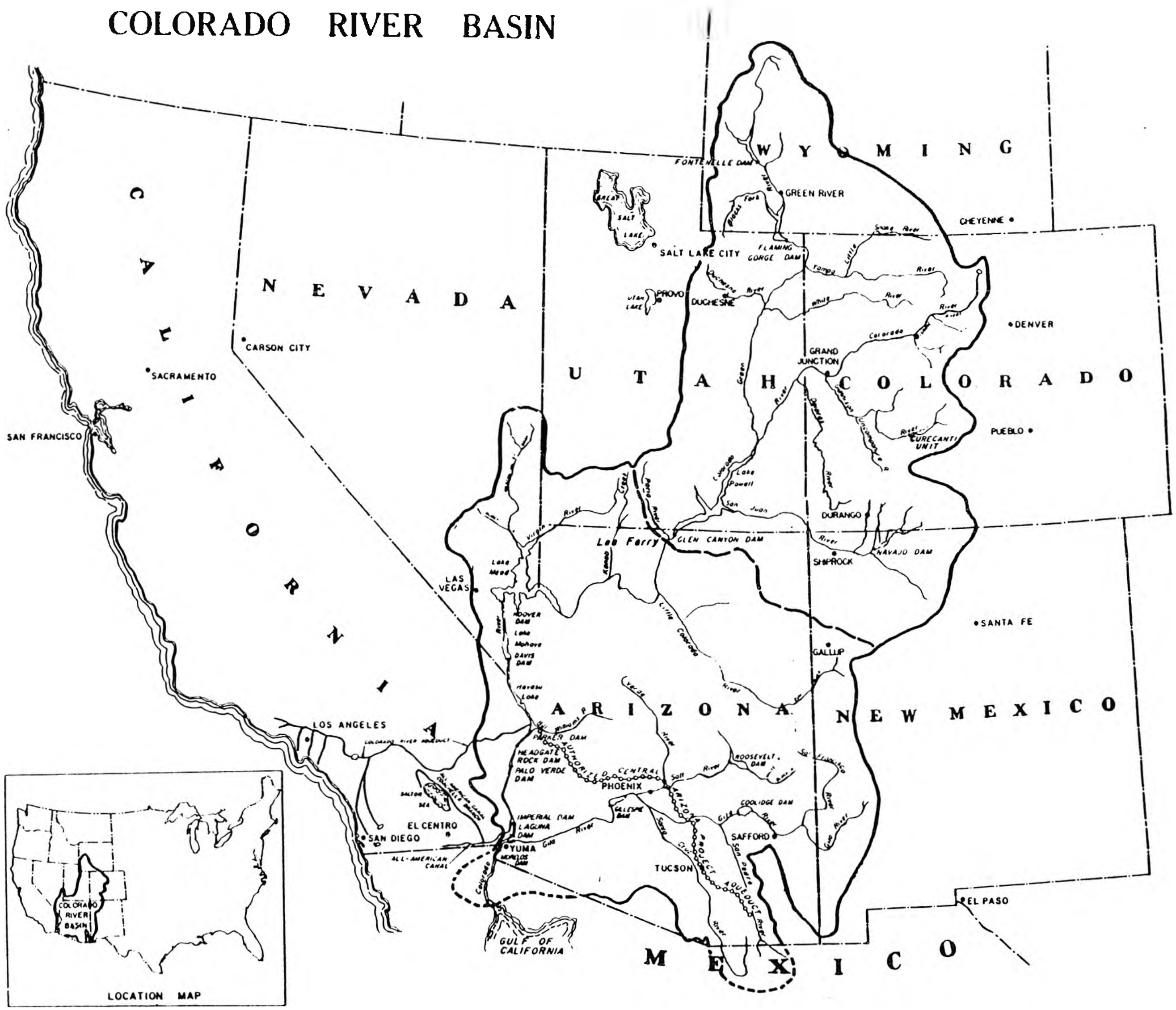

Figure 1.1 Map of the Colorado River Basin showing the upper and lower basins and major water development projects. (Source: "Annual Report for the Calendar Year 1971," Colorado River Board of California, Los Angeles, California.)

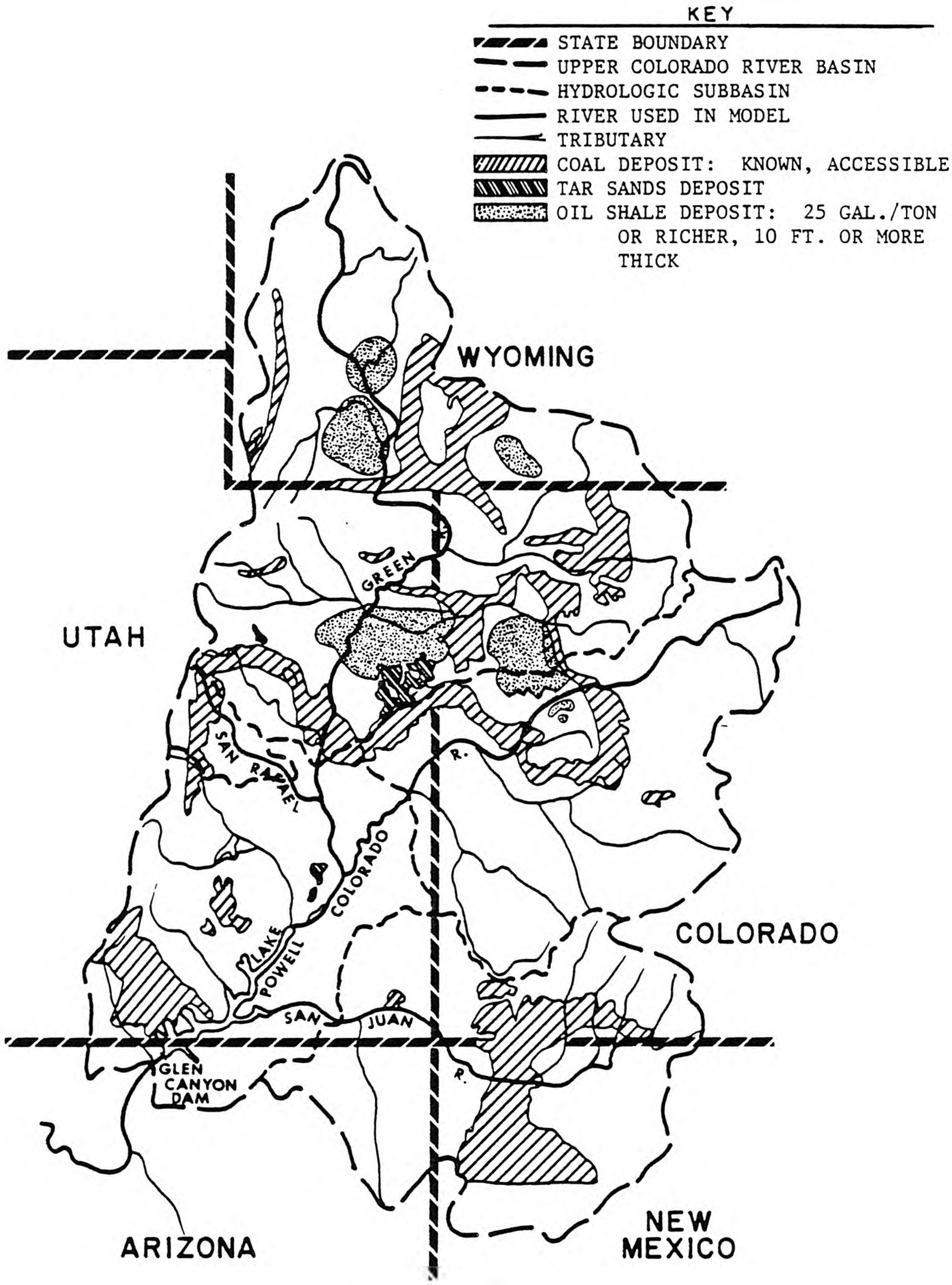

Figure 1.2 Map of the Upper Colorado River Basin showing surface hydrologic features important in this study and fossil energy resources. (Sources: U.S. Department of the Interior, 1973, Final Environmental Statement for the Prototype Oil Shale Leasing Program, Washington, D.C., August 1973. Utah Water Research Laboratory, 1975, Colorado River Regional Assessment Study, Utah State University, Logan, Utah, October 1975; prepared for National Commission on Water Quality, Washington, D. C.)

per year (5.4×10^{11} kg, Reference 2). Estimates of the high-grade resource base for oil shale (better than 25 gallons of oil recoverable from a ton of shale (1.0×10^{-4} m^3/kg)) vary from about 400 billion barrels ($6.4 \times 10^{10} m^3$), seam thickness greater than 100 ft (30 m, Reference 3), to about 600 billion barrels ($9.5 \times 10^{10} m^3$), seam thickness greater than 10 ft (3.0 m, Reference 4). Assuming a 100% recovery rate, oil from shale could replace imported oil and oil products at recent peak import rates (approximately 8 million barrels per day ($1.3 \times 10^6 m^3/d$) or 3 billion barrels per year ($4.8 \times 10^8 m^3/yr$), Reference 5) for well over 100 years. At a more reasonable recovery rate, the Office of Technology Assessment (Reference 5) has estimated imports could be replaced for 68 years.

Unfortunately, large-scale recovery of these fossil fuel resources, and conversion of them into more useful forms, could produce large-scale environmental and societal stresses. These stresses could act to constrain the resource utilization. In addition to water-related issues, these possible constraints include occupational safety and health, solid-waste management, reclamation of mined land, air pollution, increased CO_2 production, capital-and-equipment availability, skilled-labor availability, and the socio-economic effects of population changes and the "boom-town" cycle. As important as all these factors may be (see References 2 and 5-16), this report concentrates only on the water supply issue. Other factors are considered only with respect to their effects on water consumption.

Water supply in the Colorado River Basin (see Figures 1.1 and 1.2) is, itself, a very complex issue. This is because the natural runoff is relatively low and extremely variable, while the demands on the river are already very high and still growing. To give an idea of the relative quantities involved, the Colorado and Columbia Rivers drain almost equal size areas, yet the Colorado carries less than one-tenth the flow of the Columbia. The flow of the Colorado is approximately the same as that of the Delaware River whose drainage area is about one-fifteenth the size of the Colorado's (Reference 17).

Estimates of the long-term average flow in the Colorado River at Lee Ferry, Arizona, have varied from a high of 16.2 million acre-ft/yr(1) ($2.00 \times 10^{10} m^3$/yr), estimated in 1922 at the time the Colorado River Compact was established, to a low of 13.5 ± 0.5 million acre-ft/yr ($1.66 \pm .06 \times 10^{10} m^3$/yr), estimated on the basis of over 400 years of tree-ring data (Reference 18). In 1977 the total annual virgin flow is estimated to have been about 5.6 million acre-ft ($6.9 \times 10^9 m^3$), while one year later, in 1978, it is estimated to have been about 15.6 million acre-ft ($1.9 \times 10^{10} m^3$, Reference 5). Because of the arid nature of the southwest, coupled with its long growing season and sun-belt appeal, more water is exported from the Colorado River Basin than from any other basin in the United States (Reference 19), over five million acre-ft/yr ($6.2 \times 10^9 m^3$/yr), to support agriculture and

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(1) One acre-ft is the volume of water needed to cover an acre of land to a depth of one foot (1 acre-ft=3.26×10^5 gal = $1.23 \times 10^3 m^3$).

urban uses in surrounding basins (Reference 17). In addition, the river system traverses seven states and two countries.

Because of the high demand and low, variable flow, the river system is highly developed, both structurally and institutionally. In order to control the supply of the water, an extensive system of dams and reservoirs has been built on the river. The two largest reservoirs (much larger than any of the others), Lake Mead (behind Hoover Dam) and Lake Powell (behind Glen Canyon Dam), each hold about twice the average annual flow of the river.

In order to control the use of the water, a body of laws and customs has developed known as the "Law of the River." References 19 and 20 contain in-depth discussions of the Law of the River. The keystone of the Law of the River is the Colorado River Compact of 1922 which divided the Colorado River Basin into two subdivisions, the Upper Colorado River Basin (UCRB) and the Lower Colorado River Basin. The dividing line goes through Lee Ferry, Arizona (known as the Compact Point). It is located just downstream of the confluence of the Paria River with the Colorado (see Figure 1.1). The Compact apportioned use of the river's water between the two subdivisions, guaranteeing a flow of 75 million acre-ft ($9.2 \times 10^{10} m^3$) over every ten year period to the lower basin. This was done because most of the flow in the river originates in the upper basin. Since 1922 many other laws and treaties have been added to the Law of the River. One such is the Mexican Water Treaty of 1944 which guarantees at least 1.5 million acre-ft/yr ($1.8 \times 10^9 m^3$/yr) to Mexico.

Two other factors have also played a role in determining institutional controls over the river's use. The doctrine of "prior appropriation" grew up with the west as the backbone of western water law. Basically it says that appropriative rights to water are obtained by beneficially using water not previously appropriated, and that first in time means first in right. In times of drought more recent appropriators must relinquish their use so that more senior appropriators can receive their full appropriation. The second factor is that in developing the river, as in settling the west, reclaiming arid land for agriculture—the reclamation ethic—has been encouraged and subsidized.

1.2 Water-for-Energy Issues

Against the background sketched above arises the question of water supply for energy-recovery-and-conversion industries. As mentioned above, the Upper Colorado River Basin contains large reserves of fossil fuels. Large amounts of water may be needed in order to recover these fuels and convert them into forms useful to the economy. In such a heavily developed river basin as the Colorado, there is a serious question as to where the energy industries will get their water and how this will affect the rest of the water users in the basin.

Because the water for energy issue is so complex, there are many ways of looking at it. Numerous reports have been written on the engineering aspects of supplying water to individual plants or sites (e.g., Reference 6, 21 and 22). Others have dealt with supply problems in tributary subbasins (e.g., References 6, 8, and 21-26). Other authors have considered economic tradeoffs (substitution effects) with respect to water use by energy industries. Reference 27 and subsequent reports, References 28-30, discuss, in a general sense, forms of substitution such as rights purchases, types of cooling systems, water import and storage, and alternative water supplies such as ground water and municipal wastewater. References 21 and 31 consider the application of the substitution concept to individual sites. Conjunctive use of ground water with surface water,including its effect on reservoir size selection to ensure sufficient supply, is addressed in Reference 32. Microeconomic studies have been directed toward the supply-insurance issue inherent in reservoir construction and operation (References 33 and 34) and toward the operation of markets for water-rights transfers (Reference 35). On a larger scale, a number of input-output, linear-programming studies have considered the economic effects on the entire region of increased water use by energy-resource development (References 36 and 37). Water rights and other institutional issues related to water supply and use have been discussed in References 8, 19, 22, 23, and 38-40.

In addition to the quantity of supply and its allocation to off-stream users, there are also issues of in-stream use and water quality. References 41 and 42 consider, in a general way, the effects on the aquatic ecology of the region due to reduced stream flows. Many of the papers in Reference 8 consider more specific ecological issues and the impacts on other in-stream uses due to energy development. Water quality issues involve both contamination by hazardous substances (including leachates from in-situ oil-shale retorts) and the pervasive problem of salinity. Hazardous-substance pollution is considered in References 6, 11-15, 25, 26 and 43-45. Salinity issues are considered in References 6, 43, and 46-48.

The preceding studies have been concerned primarily with effects within the UCRB itself. There is, however, another dimension to the water supply issue. This is the aggregate use of water within the upper basin and its effect on water supplies to the lower basin. Even if all of the problems mentioned above could be solved, if the operation of a large energy industry in the upper basin interfered with meeting water-supply commitments to the lower basin, the viability of such an industry would be questionable. A number of reports have touched on this issue, however most (e.g. References 6, 8, 19, 49 and 50) have considered it only on an average basis and at a given point of time in the near future.

1.3 Objective and Organization of Report

This study investigates the effect of the level of energy development in the Upper Colorado River Basin on the aggregate supply of water to the Lower Colorado River Basin. It differs from most other studies of the aggregate supply issue in two ways: (1) it considers the stochastic (i.e., variable) nature of the river flows, including the effects of the two large storage reservoirs, Lakes Mead and Powell, and (2) it considers long-term water needs as a function of a steady, unchanging amount of energy resource recovery, rather than as a function of time (say in the year 2000 A.D.) for a growing energy recovery industry. Thus, this study gives conservative estimates in the sense that water-supply constraints are more severe when the reliability of supply is considered in addition to average flows, and when the long-term steady state is considered rather than a transition period during which reservoir storage above the steady state level can be utilized.

One other recent study (mandated by Congress and published by the U.S. Water Resources Council in Reference 51, but originally published in Reference 23) also takes a stochastic approach to this issue. That study, however, cannot be considered a conservative one because it deals with the transition period of an expanding energy industry and utilizes a high estimate for the average flow in the river. That study will be discussed in greater detail later.

Two limitations on the present study should be stressed at the outset: (1) it considers the UCRB as a unit, and does not address details of distribution within the UCRB; and (2) it does not deal with legal rights to water, only with current and future uses.

The following analysis is organized on the basis of determining unit water requirements for each type of energy industry (Section 2.1), and combining these with estimates of industry size (Section 2.2) to obtain total energy-related water use as a function of the total energy recovered (Section 2.3). How much energy can be recovered is then determined by examining average water availability (Section 3.1) and also the reliability of the water supply (Section 3.2). Conclusions are presented in Chapter 4.

CHAPTER 2

WATER REQUIREMENTS FOR ENERGY DEVELOPMENT

The projections of water requirements for future energy-resource development in the Upper Colorado River Basin are based on two sets of data. The first data set relates to the water consumption of different types of energy industries (e.g., coal gasification and oil-shale processing) as a function of the size of the industry; this is referred to as the unit-water-requirement data base. The second data set contains projections of size and type of energy development projects to be located in (and require water from) the Upper Colorado River Basin. This is referred to as the energy-siting-scenario data base. The water requirements for energy resource development can then be found by appropriate calculations using both data sets.

2.1 Unit-Water-Requirement Data Base

The energy industries of interest in this study are those that require relatively large amounts of water per unit of output. These include coal-electric generation, coal-slurry pipeline transport, coal gasification, coal liquefaction, oil-shale processing, and tar-sands processing. There are other energy industries that require much less water per unit of output. They will not be considered below. These include coal export by rail and recovery of naturally occurring oil and gas. Uranium recovery and processing and geothermal electric generation, although they may require significant quantities of water (References 8 and 6, respectively) are also not included.

The unit-water-requirement data base for coal gasification, coal liquefaction (direct) and oil-shale processing was developed through an extensive survey by this author of over 150 items in the open literature. It is detailed in Reference 52. For coal-electric generation, coal-slurry pipeline transport and tar-sands processing, the survey was less extensive and is detailed below. What has been found is that very few rigorous technical analyses of the energy technologies are available in the open literature. Most reports rely on water consumption rates given in earlier reports, without a critical analysis of how the rates were obtained. Some rates have passed through as many as six generations of reports over an eight-year period. In many cases, the originating reports are now as much as ten years old. Not only are the originating reports very hard to find for purposes of validation, but the technologies themselves may have changed a great deal in ten years. For each energy industry there are usually only a few main families of reports (i.e., each family stemming from the same originating reports or organization).

There is no universal agreement on the unit water consumption of a given energy industry. In addition to the possibility of different technological processes being involved (but not always stated), assumptions (also not always stated) vary widely as to such factors as upgrading of fuel product, load factor, make-up water quality, amount of non-evaporative cooling, amount of internal water recycle and water needs for off-site electricity production, mining, waste disposal and reclamation. There is also, usually, a question of whether or not associated urban use has been included. Ranges of values of water consumption are often given in the reports. Within each family of reports the ranges of the given values are fairly consistant. But, they can be quite different for different families, especially at the high water-use ends of the ranges.

It should be noted that there are currently no commercially operating synthetic fuel industries in the United States. The water use numbers found in the literature are, at best, from pilot plant experience. Therefore, even the most careful analyses are subject to question.

For the purpose of this report, a range over three characteristic water consumption values has been used for each energy industry (see Table 2.1). The lowest value corresponds to the low end of the ranges found in the reports of Water Purification Associates, Inc., (WPA), Cambridge, Massachusetts. The WPA reports contain fairly rigorous technical analyses that assume extensive onsite reuse of water. The low end numbers for coal based processes are derived under the assumption of partial air cooling. The intermediate values used in this report correspond to the high-end of the WPA ranges (usually assuming full evaporative cooling). The ranges in WPA values for oil-shale processing are primarily due to different spent-shale disposal practices. The highest values in Table 2.1 correspond to the high end of the ranges commonly found in the non-WPA literature. (Single, large outlying values have not been used.)

TABLE 2.1

Estimates of Unit Water Requirements of Energy-Resources Development Industries
(Associated Urban Use is Excluded)

UNITS: acre-ft/10^{12} Btu
($m^3/10^{12}$ J)

INDUSTRY	WPA'S LOW ESTIMATE[a]	REF. NO.	WPA'S HIGH ESTIMATE[a]	REF. NO.	GENERAL HIGH ESTIMATE	REF. NO.
Coal-Electric Generation	87 (100)	21	470 (550)	21	680 (800)	41
Coal-Slurry Pipeline	43[b] (50)	53	43[b] (50)	53	50[c] (58)	54
Coal Gasification (SNG)	37 (43)	49	91 (110)	21	530 (630)	55
Coal Liquefaction (Liquid product)	31 (36)	21	68 (79)	21	610 (720)	56
Oil-Shale Processing (Upgraded product)	55 (64)	21	95 (110)	49	100 (120)	57

[a] WPA's low estimate for coal processes assumes partial air cooling. WPA's high estimate for coal processing assumes high evaporative cooling. Difference in oil-shale processing primarily due to spent-shale disposal method. The values are from site-specific studies and include all water uses except associated urban use.

[b] Only one estimate given by WPA.

[c] Assumes 1.6 x 10^7 Btu/ton (1.9 x 10^7 J/kg) for coal, derived from Reference 16.

All values given in Table 2.1 have been converted to common units of acre-ft/10^{12} Btu ($m^3/10^{12}J$), i.e., water volume required to produce a product quantity with a total heating value of 10^{12} Btu ($10^{12}J$). Associated urban use, when explicitly given, has been excluded from the table. Associated urban use refers to the increase in urban water use caused by the population increase due to the energy industries. It is believed that none of the numbers presented in Table 2.1 include associated urban use estimates. Such estimates are approximately an order of magnitude less than the estimates for the energy industries themselves (References 6, 8, and 41). All other water uses associated with "integrated" energy industries such as those for raw resource recovery (e.g., mining) and environmental control (e.g., spent shale disposal and revegetation) are believed to be included in the WPA values given in the table. For the general high estimates, it is not always clear what water uses are included in the values or where the values come from. It should be noted that the values given in Table 2.1 are for water consumption. Because of the "zero discharge" philosophy generally held for plants to be built in the Upper Colorado River Basin, engendered by pollution control considerations, all water to be used is considered to be consumed. The final general comment on Table 2.1 is that some of the high end numbers could be for plants sited in the east. The references do not always specify siting information. Other assumptions involved in the conversion of numbers given in the literature to the common basis used in Table 2.1 can be found in Reference 52.

The WPA numbers in Table 2.1 represent the extremes of the ranges found in the major WPA reports. They were developed for upgraded products from fully integrated industries on a site-specific basis. All water uses have been included, except associated urban use. For coal-electric generation, the low WPA value is for wet/dry main condenser cooling at a North Dakota site. For wet/dry cooling at sites in the UCRB, the water consumption would be 50% to 75% higher. The high WPA value is for full evaporative condenser cooling at a site in the UCRB. The WPA coal-slurry pipeline water use value is for Gillette, Wyoming. The WPA low-end number for coal gasification water use is for outside the UCRB. For the four corners region this number (still including partial air cooling) could be as much as 60% higher. The high-use number is for the four corners region. Siting information for the WPA coal liquefaction water-use value is similar to that for gasification. For oil shale processing, the WPA low water-use number is for Paraho direct surface retorting at Rifle, Colorado. The high-use number is for TOSCO-II or Paraho-indirect surface retorting. The difference in oil-shale processing water use is primarily due to different spent shale disposal practices. All of the oil-shale processing plants employ intermediate levels of evaporative cooling.

The "general high estimate" of water consumption for coal-electric generation comes from a minisurvey of the literature summarized in Table 2.2. All of the values are for full evaporative main-condenser cooling. The 800 $m^3/10^{12}J$ value was chosen as being representative of the high end of consumption estimates for "zero discharge" plants

TABLE 2.2

Water Consumption for Coal-Electric Generation

(Selected Values from the Open Literature, Evaporative Cooling Towers, "Modern Plants" or from 2000 A.D. Scenarios)

REFERENCE	WATER CONSUMPTION ($m^3/10^{12}$ J)	COMMENT	PRIMARY CITED REFERENCE
Spofford et al., 1980 (Reference 8)	670	Eff. = 33%, includes blowdown Location: southwest	Leung & Moore, 1969[a]
Boris & Krutilla, 1980 (Reference 58)	560	Eff. = 38%, includes blowdown Location: Yellowstone basin	Leung & Moore, 1969[a]
Nat'l. Acad. Sci., 1979 (Reference 2)	400-600	Eff. = 38%	Harte & El-Gasseir, 1978 (Reference 41)
Harte & El-Gasseir, 1978 (Reference 41)	600-800 400-600	Eff. = 38%, includes blowdown Eff. = 38%, excludes blowdown	King, 1980[b] (Reference 59)
King, 1980 (Reference 59)	250-820 180-550	Eff. = 33%, includes blowdown Eff. = 33%, excludes blowdown	Calculations based on "data...suggest" and "literature estimate"
U.S. Water Res. Coun., 1978 (Reference 60)	710 850 570	Eff. = 38%, includes blowdown Heat rate = 9,600 Btu/kWh, incl bd Heat rate = 9,600 Btu/kWh, excl bd	None
West. St. Water Council, 1974 (Reference 54)	580	"Evaporative water needs"	Davis & Wood, 1974 (Reference 56)
Davis & Wood, 1974 (Reference 56)	530 or 730[c]	"Evaporative requirement"	Cootner & Lof, 1965[d]

[a]Calculation based on: Leung, Paul and Raymond Moore, 1969, "Water Consumption Determination for Steam Power Plant Cooling Towers: A Heat Mass Balance Method," Paper No. 69-WA/Pwr-3, American Society of Mechanical Engineers, New York.

[b]Cited as "in press" with page numbering different than Reference 59.

[c]Given in Table on p. 8 of Reference 56 as consumptive demand of 0.5 gallons consumed per kWh (= 530 $m^3/10^{12}$ J). Given in footnote of the table as plant water consumption at 80% load factor of 15 acre-ft/yr/MW capacity (= 730 $m^3/10^{12}$ J).

[d]Calculation apparently based on: Cootner, P.H. and G.O.G. Lof, 1965, "Water Demand for Steam Electric Generation," Resources for the Future, Washington, D.C.

(i.e., consumption includes blowdown). The National Academy of Sciences values (Reference 2) are taken from the Harte and El-Gasseir values (Reference 41) that exclude blowdown (i.e. blowdown is presumed to be returned to the stream). Also, both of these reports quote an efficiency of 38%, yet their apparent data source (Reference 59) quotes an efficiency of only 33%. Only Spofford et al. (Reference 8) and Boris and Krutilla (Reference 58) explicitly mention water uses beside main condenser cooling. The Spofford, et al., value is for a rather low efficiency plant. The Boris and Krutilla value, which is close to the WPA value, is for a more modern, high-efficiency plant, although located outside of the more arid UCRB.

The "general high estimate" of water use for coal slurry pipelines apparently comes from operating experience on an existing 18 inch (0.46 m) diameter pipeline from Arizona to Nevada (Reference 54). In reducing the number to common units, a heating value of 1.6×10^7 Btu/ton (1.9×10^7 J/kg) was chosen as being typical of the high ash content, subbituminous coal of the four corners region (Reference 16).

The "general high estimate" values for coal gasification, coal liquefaction, and oil-shale processing come from the oldest reports in which these values, which pervade the literature, first appear (see Charts 1, 6, and 11 in Reference 52).

The coal gasification water-use value comes from a U.S. Federal Power Commission report of 1973 (Reference 55). That report cites as its data source a confidential 1971 American Gas Association study (see

Reference 52). Thus a technical analysis to substantiate this value (which is approximately five times greater than the high WPA estimate) is not available in the open literature. The U.S. FPC report, however, does state that the high value is for full evaporative cooling using low quality make-up water (make-up rate being 7% of cooling water circulation rate). It also states that the number includes process, cooling, and power generation needs, as well as blowdown.

The "general high estimate" for coal liquefaction comes from a 1974 U.S. Geological Survey report (Reference 56). The low end of the range given in that report comes from a 1973 National Petroleum Council report (See Reference 52), but <u>no</u> reference is given for the high end of the range, which is an order of magnitude greater than the WPA high estimate.

The "general high estimate" for oil-shale processing comes from the U.S. Department of Interior's Environmental Impact Statement for the Prototype Oil Shale Leasing Program (Reference 57). In this report, mining, retorting, and upgrading information come from a 1971 U.S. Bureau of Mines report (see Reference 52) which did not give a detailed breakdown of water use, but did specify the equipment involved. Water use for electricity generation, spent-shale disposal and revegetation come from separate, primarily technical reports (see Reference 52).

In addition to the above energy industries, recovery and upgrading of bitumen from tar sands may also be developed in the UCRB.

Unfortunately, with respect to the UCRB, this industry is much less well developed than the other energy recovery and conversion industries. Consequently, water-use estimates for it are much less well founded. Bishop et al. (Reference 61) quote a water use for the surface processing of tar sands in the UCRB as 12 $m^3/10^{12}J$. Their source is the Record of Hearing of the Sohio Proposal before the Oil and Gas Conservation Board in Vernal, Utah, on August 28, 1974. de Nevers et al. (Reference 62) give a water use range of 52-110 $m^3/10^{12}$ J for both surface and in situ processes. Their values are based on Canadian tar-sands developers' experience and plans. Keefer and McQuivey (Reference 63) give a range for in situ extraction of 61-240 $m^3/10^{12}J$. Their values are loosely based on Shell Canada data. The upper end contains a safety factor of two. Canadian tar sands are located in a water-rich region. Because of the lack of data and development activities in the UCRB, tar-sands processing is not included in this analysis.

From the foregoing discussion and from an examination of the water use charts in Reference 52, it appears that the WPA high-estimate values, derived from careful technical analyses, are comparable to water use estimates published by actual process developers. On the other hand, the general high estimates, especially for coal gasification and coal liquefaction, are poorly founded and do not appear to represent reality, at least not for future use of fresh surface waters in the UCRB. Because the WPA high estimates consider only high evaporative cooling for coal-conversion processes and highly water consumptive methods of spent-shale disposal for oil-shale conversion processes, they should serve as reasonably conservative estimates (i.e., overpredicting use) until actual operating data from commercial installations are available.

2.2 Energy-Siting-Scenario Data Base

As difficult as it is to predict unit water usage for nonexistant industries, it is even more difficult to predict the future size of such industries. Rather than predicting the size of energy resource development in the UCRB at a specific future date (e.g., 2000 A.D.), the approach taken here is basically to set reasonable relative sizes for the different types of energy industries (held constant with time) and look at the water-availability implications of different levels of total energy output. This will serve to indicate long-term water constraints on industry size without the the need to consider such scheduling complications as capital or skilled-labor availability. One factor which must be considered, however, is energy-resource availability. Therefore, the size and geographical distribution of energy industries (the siting scenarios) used here are developed from scenarios given in the literature which appear to be, or are claimed to be, based on energy-resource availibility. The energy industry siting scenario used here is developed from the maxima of the industry sizes projected in several references. The water use for this energy siting scenario is then calculated. Water requirements for different levels of total energy output can then be determined since they would be linearly proportional to the calculated value, assuming the relative sizes of the different types of energy industries remain the same.

For the purposes of this report, five references (References 8, 23, 43, 64 and 65) have been used to construct the energy-siting-scenario data base (Tables 2.3 and 2.4). Only references whose projected water users could be disaggregated according to five specific subbasins of the UCRB were used. As mentioned in the Introduction, the stochastic nature of the Colorado River System is important in interpreting the significance of water use in the upper basin with respect to downstream flows. Therefore, the significance of the energy-related water use developed in this paper can best be interpreted in light of a stochastic hydrologic model of the river system. Details of the stochastic model whose results are used in this paper will be given below in Section 3.2.1. It is important to note here, however, that inputs to the model, including water use, are disaggregated according to five subbasins of the UCRB: Colorado Upper Mainstem, Green River, San Rafael River, San Juan River and Lake Powell (Figure 1.2). Therefore, the energy-siting scenarios have been disaggregated according to these five subbasins.

All of the references used here were published since 1978, and all but one of the future scenarios are projections to the year 2000. Reference 64 is the exception. Its projection is based on all energy facilities actually under construction, planned or proposed by industry as of 1978. The information in Reference 64 comes from personal communications with local Bureau of Mines personnel, environmental

TABLE 2.3

Energy Siting Scenarios from the Open Literature, Upper Colorado River Basin -- Year 2000 [a]
(Includes Only Major Water-Consuming Technologies)

INDUSTRY	REFERENCE NO	COLORADO MAINSTEM	GREEN RIVER	SAN RAFAEL RIVER	SAN JUAN RIVER	LAKE POWELL	TOTALS
Coal-Electric Generation [MW]	64&65[b]	110	5210- 5710	2490	6170- 6270	7410	21390-21990
	23[c]	570-1880	8810-12250	1660	3260- 4650	2040- 2140	16340-22580
	43	---	5790	2075	4550	3000	15415
	8	250-2350	4850-11840	1600	5300-11300	750-10850	12750-37940
Coal-Slurry Pipeline [10^6tons/yr]	64	---	---	---	9	11.4[d]	20.4
	23	---	---	---	---	---	---
	43	---	---	---	---	11.4[d]	11.4
	8	---	---	---	---	---	---
Coal Gasification (High-Btu) [10^6scfd]	64	---	---	---	1785	864	2649
	23	---	250- 750	---	1750- 1785	---	2000- 2535
	43	---	250	---	1785	---	2035
	8	---	0- 4000	---	0- 2750	0- 3000	0- 9750
Oil-Shale Processing [10^3bpd]	64	70- 80	250- 500	---	---	---	320- 580
	23	200- 500	1100- 1940	---	---	---	1300- 2440
	43	200	1100	---	---	---	1300
	8	0- 550	0- 3100	---	---	---	0- 3650

[a] All energy industries are considered to be users of the fresh surface waters of the subbasins in which they are sited, even if current plans are for their using groundwater.

[b] Sum of current capacity given in Reference 65 and future capacity additions given in Reference 64.

[c] May include nuclear power plants. Listed as thermal electric generation as given by state estimates, see text.

[d] Possibly located outside of, but adjacent to Upper Colorado River Basin.

impact statements, trade journals, electric coordinating councils, public utilities commissions, the Federal Power Commission, and other local and federal agencies. Since Reference 64 does not include electric generating capacity already in place as of 1978, all large coal-electric generating facilities in existence pre-1978, as reported in Reference 65, have been added to its projections. This consists of 1,300 MW constructed prior to 1969 and 7,900 MW constructed since 1969.

The projections in Reference 23 for electric generation come from state estimates. No indication is made as to whether any nuclear capacity is included. The data were given in the form of total capacity for the entire UCRB and water use distributed in the subbasins. To distribute the capacity to the subbasins it was assumed that all plants (including those already in place) are coal fired and use the same amount of water per unit output (i.e., have the same heat rates and load factors). The projections for coal gasification and oil-shale processing come from regional totals supplied by the U.S. Department of Energy.(2) According to Reference 23 they are based on a national fuel-demand projection with the amount credited to synthetic fuels decided "more or less arbitrarily." The regional totals were then apportioned to subbasins by the Colorado Department of Natural

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(2) Though not stated explicitly in Reference 23, the reference for this is probably: U.S. Department of Energy, 1978, <u>Energy Supply Projections (1985 and 2000) and Emerging Energy Technology Characteristics for Section 13(a) Water Assessment</u>, January, 1978.

Resources on the basis of energy-resource availability and existing developers' plans.

The projections in Reference 43 also come from the U.S. Department of Energy (Energy Research and Development Administration, at the time). In fact, it is possible that Reference 43's source[3] is ultimately the same as that of Reference 23, since some of the numbers for coal gasification and oil-shale processing are the same (see Table 2.3).

The projections in Reference 8 are primarily based on 1978 projections to the year 2000 for the four-corners states (Reference 66), which, in turn, are based on national totals given in an unpublished Resources for the Future paper. Subbasin projections are somewhat arbitrary extrapolations of industry plans, but are claimed to be founded on an adequate energy resource base (Reference 66). As can be seen in Table 2.3, the high ends of Reference 8's ranges for all energy industries (excluding slurry pipelines) are much higher than those given in the other projections. According to Reference 8 these high-end numbers represent a national commitment to synthetic-fuels development on the order of the Manhatten Project. Under such circumstances the allocation of water resources would probably be of secondary importance. Therefore, the projections given in Reference 8

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(3) Goettle, R.J., J. Brainard and I. Bhasin, 1977, A Regional Disaggregation of ERDA's Forecast 2 Energy Scenario for the Year 2000, BNL 22538, Brookhaven National Laboratory, March, 1977; prepared for the U.S. Water Resources Council.

have not been used directly in this report. They indicate, however, a coal and oil-shale resource base large enough to support at least a 12 quad/yr (1.3 x 10^{19} J/yr) energy recovery industry.[(4)]

The siting information contained in the references was segregated by energy industry and geographic subbasin (Table 2.3 and Figure 1.2). For each type of industry and subbasin, the industry size selected for use in this analysis was the highest value found in any report, excluding Reference 8. These values are shown in Table 2.4. Also in Table 2.4, traditional units have been converted to more comparable units based on the energy content of an industry's annual production. In converting units, a 70% load factor (fraction of time, on an annual basis, an industry is operating at full capacity) was assumed for coal electric generation. This is a typical value for modern coal-fired, base-load plants (Reference 53). For the other energy industries a load factor of 100% was assumed. It is estimated that the load factor for coal slurry pipelines will be nearly 100%, but for the synthetic fuel processes it will probably be closer to 90% (Reference 53). Nevertheless, a load factor of 100% was used for the synthetic fuel processes because the references containing the siting scenarios are vague concerning load factors. Some appear to use calendar days while others appear to use stream days. In any case, since the unit-water-requirement data base is given in terms of water use per unit

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(4) 1 quad = one quadrillion Btu = 1.0 x 10^{15} Btu = 1.05 10^{18} J.

TABLE 2.4

Energy Siting Scenario Used in this Report for Upper Colorado River Basin (Capacity and Energy Content of Annual Production)[a]

INDUSTRY	UNITS	COLORADO MAINSTEM	GREEN RIVER	SAN RAFAEL RIVER	SAN JUAN RIVER	LAKE POWELL	TOTALS[b]
Coal-Electric Generation	[MW]	[1880]	[12250]	[2490]	[6270]	[7410]	[30300]
	10^{12}Btu/yr	39	250	52	130	150	630
	(10^{15}J/yr)	(41)	(270)	(55)	(140)	(160)	(660)
Coal-Slurry Pipeline	[10^6 tons/yr]				[9.0]	[11.4]	[20.4]
	10^{12}Btu/yr	---	---	---	150	190	340
	(10^{15}J/yr)				(160)	(200)	(360)
Coal Gasification (SNG)	[10^6 scfd]		[750]		[1785]	[864]	[3399]
	10^{12}Btu/yr	---	260	---	630	300	1200
	(10^{15}J/yr)		(280)		(660)	(320)	(1300)
Oil-Shale Processing	[10^3bpd]	[500]	[1940]				[2440]
	10^{12}Btu/yr	1100	4100	---	---	---	5200
	(10^{15}J/yr)	(1100)	(4300)				(5400)
TOTALS[b]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
	10^{12}Btu/yr	1100	4600	52	910	650	7300
	(10^{15}J/yr)	(1200)	(4900)	(55)	(950)	(680)	(7700)

[a]Values are from maxima of ranges given in Table 2. Values from Reference 8 have not been used, see text. Conversion to annual energy basis assumed 70% load factor for coal electric generation and 100% load factor for other energy industries, see text. Heating values assumed were: 1.6×10^7Btu/ton (1.9×10^7J/kg) for slurry pipeline, 9.6×10^2Btu/scf (3.6×10^7J/m^3) for gasification and 5.8×10^6Btu/bbl (3.8×10^{10}J/m^3) for oil shale (all derived from Reference 49). All converted values are rounded to two significant figures.

[b]Errors in sums due to rounding.

energy production (not capacity), the end result of annual water consumption for annual energy production will be correct.

None of the references considered above contain projections of coal liquefaction developments. The CONAES Report of the National Academy of Science (Reference 2) has identified the production of liquid fuels as a critical national priority. Because coal liquefaction was not considered explicitly by the references, it will not be considered explicitly in this report. However, because they both depend on the same resource base—coal—and use approximately the same amount of water per unit energy of product, coal liquefaction plants can be considered, in some sense, as substitutes for the coal gasification plants included in this analysis.

2.3 Water Consumption for Energy Development

The projection of annual water consumption by energy industries in the Upper Colorado River Basin was computed by multiplying the appropriate water consumption per unit energy of product (from the unit-water-requirement data base) by the appropriate size of the industry in terms of the energy content of its annual production, in each geographic subbasin (from the energy-siting-scenario data base). For each energy industry in each subbasin, a range over three water usage rates was calculated, see Tables 2.5a and 2.5b. The tables are the same, except that Table 2.5a is in units of 10^3 acre-ft/yr and Table 2.5b is in units of $10^6 m^3$/yr. The low water-use rate (L) is derived from the lowest unit-water-consumption estimates (WPA's low

TABLE 2.5a

Estimates of Water Consumption by Energy Industries
Upper Colorado River Basin
(Does Not Include Associated Urban Use)

UNITS: 10^3 acre-ft/yr

INDUSTRY	CASE[a]	COLORADO MAINSTEM	GREEN RIVER	SAN RAFAEL RIVER	SAN JUAN RIVER	LAKE POWELL	TOTALS[b]
Coal-Electric Generation	L	3.4	22	4.5	11	13	55
	M	18	120	24	61	72	300
	H	27	170	35	88	100	430
Coal-Slurry Pipeline	L	---	---	---	6.4	8.1	15
	M	---	---	---	6.4	8.1	15
	H	---	---	---	7.2	9.1	16
Coal Gasification	L	---	9.7	---	23	11	44
	M	---	24	---	57	28	110
	H	---	140	---	330	160	630
Oil-Shale Processing	L	58	230	---	---	---	280
	M	100	390	---	---	---	490
	H	110	410	---	---	---	520
TOTALS[b]	L	62	260	4.5	41	33	400[c]
	M	120	530	24	120	110	910
	H	130	720	35	430	270	1600

[a] L = (WPA low unit-water-use estimate) x (siting estimate), M = (WPA high unit-water-use estimate) x (siting estimate), H = (general high unit-water-use estimate) x (siting estimate).

[b] Errors in sums due to rounding.

[c] Partial air cooling assumed for all electric generation.

TABLE 2.5b

Estimates of Water Consumption by Energy Industries,
Upper Colorado River Basin
(Does Not Include Associated Urban Use)

UNITS: 10^6 m^3/yr

INDUSTRY	CASE[a]	COLORADO MAINSTEM	GREEN RIVER	SAN RAFAEL RIVER	SAN JUAN RIVER	LAKE POWELL	TOTALS[b]
Coal-Electric Generation	L	4.1	27	5.4	14	16	66
	M	23	150	30	76	89	360
	H	33	210	44	110	130	530
Coal-Slurry Pipeline	L	---	---	---	7.9	10	18
	M	---	---	---	7.9	10	18
	H	---	---	---	8.8	11	20
Coal Gasification	L	---	12	---	28	14	54
	M	---	30	---	73	35	140
	H	---	170	---	420	200	790
Oil-Shale Processing	L	71	280	---	---	---	350
	M	120	480	---	---	---	600
	H	130	520	---	---	---	650
TOTALS[b]	L	76	320	5.4	50	40	490[c]
	M	150	650	30	160	130	1100
	H	170	910	44	530	340	2000

[a]L = (WPA low unit-water-use estimate) x (siting estimate), M = (WPA high unit-water-use estimate) x (siting estimate), H = (general high unit-water-use estimate) x (siting estimate).

[b]Errors in sums due to rounding

[c]Partial air cooling assumed for <u>all</u> electric generation.

estimate); the medium rate (M) from the intermediate unit-water-consumption estimate (WPA's high estimate); and the high rate (H) from the highest unit-water-consumption estimate (general high estimate). In addition, Tables 2.5a and 2.5b show total water use for all water-intensive energy developments in each subbasin, for each energy industry in the entire Upper Colorado River Basin, and for all water-intensive energy-resource development in the entire Upper Colorado River Basin.

With respect to the three levels of consumption considered in Tables 2.5, the low (L) estimate is probably a lower limit for the level of development considered because of the site-specific nature of the WPA values, and because of the assumption of partial air cooling in all geographic areas, and even for electric generating capacity already in place. The high (H) estimate is probably too high due mainly to the high, questionable water demand for coal-electric generation and to the very high, very questionable water demand for coal gasification. The medium (M) estimate can be considered a conservative "best guess" at this time.

The "M" estimate can be considered a conservative best guess in the sense of erring on the side of overpredicting water use. This is partly because the highest WPA values for high evaporative cooling were used. Because of the "zero discharge" nature of the plants now being built in the arid west, industry is becoming very sensitive to the costs incurred from having to dispose of large quantities of cooling-tower blowdown (References 29 and 67). This should encourage high rates of in-plant recycle and use of partial air cooling. Using the high WPA estimates also ignores all other forms of substitution for high quality surface water, such as use of reclaimed urban waste water or low quality ground water. The "M" case is also possibly an overestimate of water use because of the high proportion of electric generation considered, the most water intensive energy industry. In fact, oil-shale processing, coal gasification and coal liquifacton all use roughly the same amount of water per unit energy of output product and can almost be thought of as substitutes for each other in a water use sense.

Because this analysis is meant to be a conservative one, it will rely primarily on the "M" estimate, i.e., a conservative "best guess". At the risk of not being conservative, it is also possible to hazard a "best guess" for water consumption by synthetic-fuel developments and coal-electric generation in the 21st century. The following estimates are made under two general assumptions: (1) that "zero discharge" of waste water is the rule and (2) that use of wet/dry cooling on steam-turbine condensers is standard practice. From an examination of the WPA charts in Reference 52 for all technologies and intermediate levels of wet cooling, it appears that a best guess for both SNG coal gasification and oil-shale processing might be about 80 $m^3/10^{12}J$, while for coal liquefaction it would be about 60 $m^3/10^{12}J$. The high end of ranges for bituminous and subbituminous coals were considered because these were derived for sites in the UCRB. Therefore, as a "rule of thumb" for water consumption by synthetic fuel development in the UCRB, a best guess would be 80 $m^3/10^{12}J$ and a <u>conservative</u> best guess would be 110 $m^3/10^{12}J$. For coal-fired electric power plants, because of the much larger cooling load than in synthetic fuel plants, wet/dry cooling will probably be a more expensive option and will be more dependent on water availability and transport and storage costs. Based on an arbitrary assumption that one-half of the installed capacity would use optimum wet/dry cooling and the other half would use full wet cooling, the average water consumption for coal electric generation in the UCRB (from values given in Reference 21) would be about 360 $m^3/10^{12}J$. Combining these unit water uses with the siting scenario used above results in an annual consumption of 790 x 10^6 m^3/yr. This is 72% of the conservative best-guess value (the "M" estimate) and lies about midway between the "M" and "L" estimates derived above.

Including a 10% increment for associated urban use along with the reasonably <u>conservative</u> best-guess "M" estimate, implies that approximately 7.3 quads per year (7.7 x 10^{18} J/yr) could be produced from the fossil-energy resources of the Upper Colorado River Basin by major water-intensive industries at a cost of about one million acre-ft/yr (1.2 x 10^9 m^3/yr) of water. This is approximately equivalent to 3.9 million barrels per day (6.2 x $10^5 m^3$/d) oil equivalent (bpdOE), which was about one-half liquid fuel imports or roughly one tenth of total U.S. energy consumption in 1978 (Reference 2). Current liquid fuel imports are substantially less. The above conversions assume 365 days per year, 6.0 x 10^6 Btu per barrel, that synfuels and exported coal are direct replacements for oil, and that electricity from coal is a replacement for the oil that would have been burned in power plants and so is multiplied by a factor of three to compensate for the efficiency of conversion. If there were only one-half the electricity production as estimated in the energy siting scenario, and the same amount of coal slurry pipeline transport, then for about the same water use, increased synfuel production could boost total energy output to about 8.5 quads per year (9.0×10^{18} J/yr), or 4.2 million barrels oil equivalent per day (6.7×10^{5} m^3/d).

The above estimate of energy recovery includes only industries which are considered to be major water consumers. Other energy industries which consume appreciably smaller quantities of water per unit energy of product have not been considered. Such industries as coal export by rail, uranium mining and processing, and the recovery of naturally occurring petroleum and natural gas could add a great deal to the energy recovered from the region for only a small increase in water consumption.

CHAPTER 3

AGGREGATE WATER AVAILABILITY FOR ENERGY DEVELOPMENT

In considering water availability for energy development in the Upper Colorado River Basin, it is necessary to consider the effect of the energy development on the reliability of supply to the lower basin as well as on average flows.

3.1 Average Flows

3.1.1 Water Available to the UCRB

On an average basis, there appear to be approximately 4.8 million acre-ft/yr ($5.9 \times 10^9 m^3$/yr) available for all consumptive uses, over and above evaporation from reservoirs, in the upper basin. Although the average natural, undepleted flow[(5)] into Lake Powell would be approximately 13.5 million acre-ft/yr ($1.66 \times 10^{10} m^3$/yr), this is not the amount of water available for use in the Upper Colorado River Basin. There are many legal and institutional controls on Colorado River water availability (including the Colorado River Compact of 1922

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(5) The time period used to determine UCRB flow statistics for this report is the same as in Reference 17, 1931-1969. There is a great deal of controversy over what period should be used. Historic periods starting earlier tend to give higher flows. Some investigators believe this is because there are long term climatic cycles affecting the flows. If this is true, the period 1931-1969 may be a minimum flow period, and results based on it may be overly conservative. There are not enough data available at present, however, to be able to prove this. Tree-ring studies (Reference 18) indicating a 400 year average flow of $13.5 \pm .5$ million acre-ft/yr ($1.66 \pm .06 \times 10^{10} m^3$/yr) and the drought of 1976-77 tend to indicate it is not overly conservative.

and the Mexican Water Treaty[(6)] of 1944 (see Reference 17 for a brief summary and Reference 20 for a longer discussion). Because of these, there is an annual target discharge from Lake Powell of approximately 8.23 million acre-ft/yr ($1.012 \times 10^{10} m^3$/yr), so that 8.25 million acre-ft/yr ($1.015 \times 10^{10} m^3$/yr) will flow into the lower basin when side inflows below Glen Canyon Dam are included. Therefore, considering an average evaporation from Lake Powell of 0.5 million acre-ft/yr ($6.15 \times 10^8 m^3$/yr, Reference 17), there are, on the average, only about 4.8 million acre-ft/yr ($5.9 \times 10^9 m^3$/yr) available for use in the upper basin.

3.1.2 Energy Development and Average Flows

As shown in Chapter 2, the production of 7.3 quad/yr (7.7×10^{18} J/yr) by water-intensive energy industries would require between 0.40 and 0.91 million acre-ft/yr ($0.49\text{-}1.12 \times 10^9 m^3$/yr) exclusive of associated urban use. The range is due to differences in technologies used, in the amount of dry cooling employed and in site specific environmental variables. Considering the upper end of the range to be conservative and adding 10% to cover associated urban use, 7.3 quad/yr

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(6) There is also controversy over how much of the water promised to Mexico is the responsibility of the upper basin (Reference 23). The assumption made in this report, as in Reference 17, is that the upper basin is responsible for the release of 0.75 million acre-ft/yr ($9.2 \times 10^8 m^3$/yr) over Compact obligations of 7.5 million acre-ft/yr ($9.2 \times 10^9 m^3$/yr) as its portion of the Mexican Water Treaty obligation. This is the current operating policy on the river (U.S. Department of the Interior, "Colorado River Reservoirs, Coordinated Long-Range Operation," Federal Register, Vol. 35, No. 112, 1970, pp. 8951-8952).

(7.7×10^{18} J/yr) could be recovered for a water expenditure of about 1.0 million acre-ft/yr (1.2×10^9 m^3/yr). This is itemized in Table 3.1 and shown graphically in Figure 3.1. Also shown in the figure is how this water use would vary with different levels of <u>total</u> water-intensive energy production, assuming that the fraction of total energy produced by each industry sector is kept constant.[7] What is shown in the figure are <u>increases</u> in annual water consumption over the current level in the upper basin due only to energy development as a function of total energy output from water-intensive energy industries (i.e., coal-electric generation, coal-slurry pipeline export, coal-synfuel production and oil-shale processing). Present upper basin consumption is approximately 3.0 million acre-ft/yr ($3.7 \times 10^9 m^3$/yr), exclusive of reservoir evaporation and electricity generation, with its associated urban use—see Table 3.1. Present electric generation is excluded from present uses because it is included in the projections of increased production. Although energy use is shown as an increment to present non-energy uses, this should not be considered a recommendation for changing or not changing current uses. On an average basis, accepting a maximum permitted average use of 4.8 million acre-ft/yr ($5.9 \times 10^9 m^3$/yr) in the UCRB, the 7.3 quad/yr (7.7×10^{18} J/yr) scenario would allow a minimum total increase of 0.8 million acre-ft/yr ($9.8 \times 10^8 m^3$/yr) over current usage for all non-energy related purposes in the

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(7) Actually it is the ratio of coal-electric generation to synfuel production which must be kept constant, since slurry pipelines are a very minor use and all synfuel industries use roughly the same amount of water on a per unit energy output basis.

upper basin. For lower values of energy output, non-energy related water uses could be greater, while for higher values of energy output they would have to be lower (Figure 3.1).

Table 3.1 and Figure 3.1 are also useful for comparing the results of the present study to those of two other recent studies related to energy development in the UCRB. These studies were done by the U.S. Water Resources Council, Reference 51, and by EXXON Company, U.S.A., Reference 69. The Water Resources Council projection includes all other additional uses of water (including irrigation and export) as well as that for energy production. The EXXON projection is only for synthetic fuel production. It does not include irrigation, export or even coal-electric generation. A ten percent increase has been added to the synfuel water use given in Reference 69 to account for associated urban use, thus making the figure consistant for all three analyses. EXXON's water use range is indicated by the wavy border.

The U.S. Water Resources Council (Reference 51) took its data directly from Reference 23. It should be noted, however, that the level of non-synfuel related development projected for the year 2000 A.D. in Reference 51 is the "medium" level projected for these activities in Reference 23. The level of energy development in the Water Resources Council study is similar to the case used for calculation purposes in the present paper. In fact, the level of oil-shale development is identical since, in both cases, it came from Reference 23 (see Tables 2.3 and 2.4). The level of coal gasification and coal-electric generation are lower than in the present analysis.

TABLE 3.1

Upper Colorado River Basin Annual Water Consumption[a]

UNITS: 10^6 acre-ft/yr[b]

USE SECTOR	CURRENT USE		FUTURE USE		
	U.S. Bureau of Reclamation (Ref. 68) for 1980 A.D.	U.S. Water Resources Council (Ref. 51) for 1981 A.D.[c]	Caltech (This study)	U.S. Water Resources Council (Ref. 51) for 2000 A.D.	EXXON Co., U.S.A. (Ref. 69) for 2000 A.D.
ENERGY[d]		0.074	0.40-0.91 (≈7.3 quad/yr or 3.9×10^6 bpdOE)[f]	0.685 (≈6.5 quad/yr or 3.3×10^6 bpdOE)[f]	0.8-1.6 (≈19 quad/yr or 8.7×10^6 bpdOE)[f]
ASSOC. URBAN USE	2.44	---	0.04-0.09	0.068[g]	---
MUNICIPAL & INDUSTRIAL[e]		0.133		0.286	---
AGRICULTURE		2.145	4.4 -3.8	2.736	---
EXPORT	0.64	0.764		1.149	---
TOTAL	3.08	3.116	4.8	4.924	---

[a]Exclusive of reservoir evaporation

[b]1.00 acre-ft/yr = 1.23×10^3 m^3/yr.

[c]Data from Reference 23 which cites 1975 and 1976 as base years for data.

[d]Includes coal-electric generation (except in EXXON report, Reference 69), coal gasification (and/or liquefaction in EXXON report, Reference 69), coal-slurry pipeline (this study only) and oil-shale processing.

[e]Exclusive of energy and associated urban use.

[f]End-product energy produced. In converting from quad/yr to bpdOE, synfuels and coal exports were considered direct replacements for oil, electricity production was multiplied by a factor of three to compensate for oil replaced in power plants, and it was assumed one barrel oil equivalent contains 6×10^6Btu and one year=365 days (1 quad = 1.00×10^{15} Btu=1.055×10^{18} J, 1 barrel = 1.59×10^{-1} m^3).

[g]For synfuels only. Associated urban use for electricity production may be in municipal and industrial use.

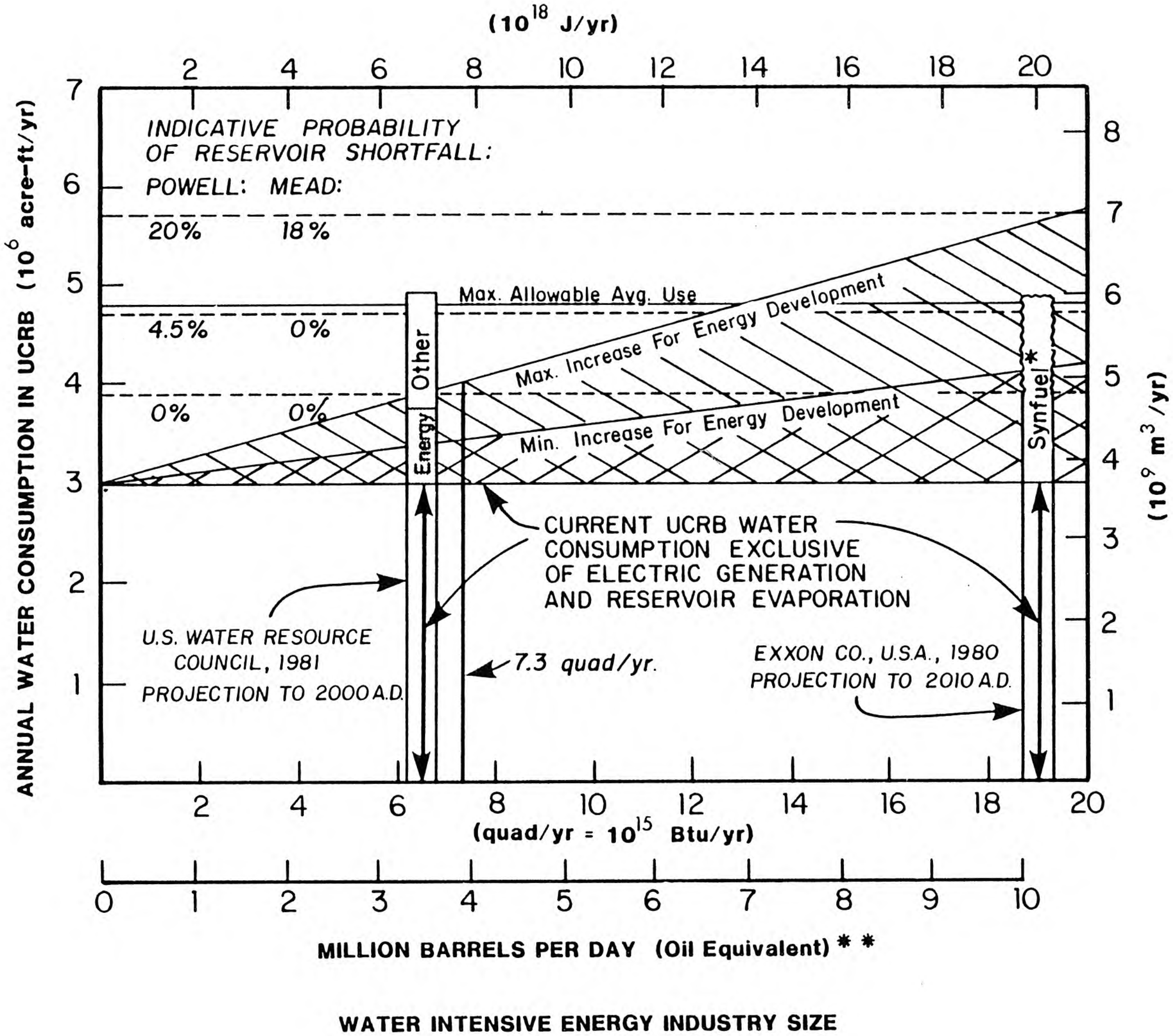

Figure 3.1 Increase in annual water consumption in the Upper Colorado River Basin (UCRB) over current levels as a function of water-intensive energy industry size. Associated urban use is included. Reservoir evaporation is not shown, but included implicitly. Energy industry composition, based on product energy content: 9% coal-electric generation, 4% coal-slurry pipeline, 17% SNG coal gasification, 70% oil-shale processing. *Range (wavy border) due to stated range in unit water requirements. ** Conversion assumes 6.0×10^6 Btu per barrel; electricity is multiplied by three to compensate for conversion efficiency.

Another major difference is that the unit water use for oil-shale processing used in Reference 51 is approximately 40% lower than that used in the present work. It can be seen from Figure 3.1 that, based on a total of 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) being available to the UCRB, the upper basin will have trouble meeting all of the year 2000 water needs as projected by the Water Resources Council, even on an average basis. It should be mentioned that the Council's report makes use of a river simulation based on the 1906-1974 period of record. This yields an average flow of 15.2 million acre-ft/yr (1.87 x $10^{10} m^3$/yr), and thus an average availability to the upper basin of 6.5 million acre-ft/yr (8.0 x $10^9 m^3$/yr).

The EXXON report (Reference 69) is a projection of possible national synthetic-fuel developments to the year 2010 A.D. The emphasis is on replacing imports of liquid hydrocarbons. Electricity production is not considered. Within the UCRB, oil-shale processing is projected to produce 8.0 million barrels per day (1.3 x $10^6 m^3$/d) oil equivalent, and coal processing an additional 0.7 million barrels per day (1.1 x $10^5 m^3$/d) oil equivalent. Water use is estimated at between two and four barrels of water per barrel of oil equivalent. Four barrels per barrel oil equivalent is approximately 86 acre-ft/10^{12} Btu (100 $m^3/10^{12}$J) which is just slightly less than the higher unit-water-use value used in this study (WPA's high estimate, without associated urban use). Combining the high end of the water use range from EXXON's synfuel projections, 1.6 million acre-ft/yr (2.0 x $10^9 m^3$/yr), with total current water use in the UCRB(3.1 million acre-ft/yr (3.8 x

$10^9 m^3$/yr) including electricity production), results in a value that approaches the 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) available to the upper basin and leaves very little for increases in any other activities in the basin. The significance of the Water Resource Council and EXXON projections will be returned to in the following section where the reliability of water supply is considered.

3.2 Reliability of Water Supply

Unfortunately, long term average numbers do not determine the year-to-year reliability of the water supply. Flows in the tributaries of the Colorado River are extremely variable with time--easily changing by a factor of two from one month to the next or from one year to the next.

The presence of two very large reservoirs on the river, Lakes Powell and Mead, downstream of the upper basin tributaries but upstream of almost all lower basin demand, helps a great deal in regularizing the flow of water to lower basin users. It is possible, however, that a sequence of drought years could cause a shortfall from one or both of these large reservoirs (i.e., a failure to release enough water to cover all of its downstream obligations, its "target release"). Therefore, although on a long term average basis there might be 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) available for use in the upper basin, during some years the use of 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) could cause reservoir shortfall or "failure". This is why it is important to consider the variable nature of the flows on downstream supply reliability.

3.2.1 Stochastic Hydrologic Models

Stochastic hydrologic models are used for studying river and reservoir systems with variable input flows. For given sequences of input flows the models can predict the fraction of years reservoirs will fail to meet target releases. Different input sequences with the same gross statistics (i.e., average flow and standard deviation) can produce quite different occurences of reservoir failure depending on their patterns of high and low flows. Therefore, reservoir failure can be predicted no better than the inflow sequence can be predicted. Stochastic hydrologic models, however, can function to indicate the increase in the relative risk of reservoir failure as upstream depletions (consumptive uses) are increased.

The stochastic hydrologic model employed in this study was developed by Arthur R. Jensen at Caltech. Details of the model can be found in Reference 17, from which the following description has been adapted. The model generates synthetic sequences of streamflow and total dissolved solids (TDS) concentrations in the major upper basin tributaries: Upper Colorado Mainstem, Green River, San Juan River and San Rafael River. The last tributary is important because of its salt load. The flows of water and TDS are then routed through the two major reservoirs of the system, Lakes Powell and Mead. Generation of synthetic tributary streamflow sequences is performed using a lag-one autoregressive Markovian model of the form developed by Thomas and

Fiering.[8] The monthly streamflows generated embody the serial and cross-correlation characteristics of the recorded flows and are statistically indistinguishable from the historical sequences. The period of record used is 1931-1969. The mass routing of water through the reservoirs includes the effects of evaporation as a function of reservoir storage and the month of the year. Reservoir operation, the scheduling of releases, is performed according to the linear release rule, the goal of which is meeting set target discharges whenever possible.[9] Once the target discharge for each period is met, excess water goes to reservoir filling. The reservoirs are operated independently. The model is operated in a stationary mode, which means that depletions (consumptive uses) are held constant on a yearly basis and the simulations are run for sufficient years for the effects of initial conditions to die out. Thus the model is not good for examining short-run, transitory behavior, but only for indicating long-run, steady state trends.

In several ways this model differs considerably from the actual river system and from more detailed models of the system such as the

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(8) Thomas, H.A., Jr. and M.B. Fiering, 1962, "The Mathematical Synthesis of Streamflow Sequences," The Design of Water Resource Systems, Arthur Maas, et al. (eds.), Harvard University Press, Cambridge, Massachusetts.

(9) The linear release rule is unrealistic as reservoir storage approaches zero, because it implies using as much water as there is (up to the target release rate); in reality, it would be released more slowly as complete emptiness is approached. For the purposes of the analysis, however, the linear rule is adequate.

U.S. Bureau of Reclamation's CRSS model (Reference 70). The CRSS model was used in the Water Resources Council study (References 51 and 23). The model used in the present study contains the following simplifications: (1) All depeletions on a tributary are aggregated so it is not possible to determine "local" supply problems. (2) Tributary reservoirs are not included since their effects on lower basin supply are minor compared to Lakes Powell and Mead. (3) Reservoir operation in the model ignores stream-flow forecasting which is used in real systems to adjust releases for flood control and electric power production reasons. (4) The reservoirs are operated independently. (5) The linear release rule for reservoirs is used exclusively. As shown by Jensen (Reference 17) these differences should not significantly influence the steady-state results for aggregate flow. There is, however, a question as to the adequacy of 40 years of reliable calibration data to provide sufficient information regarding the frequency of extreme river flows, which produce the extremes in reservoir discharge. Thus, information on probabilities of reservoir shortfall should be viewed carefully and best used only for comparative purposes.

3.2.2 Energy Development and Reliability of Supply

In Reference 17, Jensen reported simulation results for three levels of Upper Colorado River Basin total depletions (consumptive uses): 3.9, 4.7 and 5.7 million acre-ft/yr (4.8, 5.8 and 7.0 x $10^9 m^3$/yr). The breakdown of these depletions by subbasin and user classification is given in Table 3.2. The three user classifications

TABLE 3.2
Comparison of Water Consumption Scenarios with Historic Uses and Flows, Upper Colorado River Basin[a]

UNITS: 10^3 acre-ft/yr[b]

SCENARIO	TYPE OR LEVEL OF NET USE	COLORADO MAINSTEM	GREEN RIVER	SAN RAFAEL RIVER	SAN JUAN RIVER	LAKE POWELL	TOTALS
Average Natural Flow[c] (1931-1969)	none	6770	4285	95	1887	492[d]	13529
Base-Line Use[c] (1965-1970)	Muni. & Ind.	36	12	0	36	15	99
	Irrig.	932	818	0	378	0	2128
	Exports	424	122	0	3	0	549
	TOTALS	1392	952	0	417	15	2776
Jensen, DPL Level #1[c]	Muni. & Ind.	84	162	5	56	50	357
	Irrig.	936	818	0	658	0	2412
	Exports	701	304	0	113	0	1118
	TOTALS	1721	1284	5	827	50	3887
Jensen, DPL Level #2[c]	Muni. & Ind.	160	282	5	56	152	654
	Irrig.	1086	890	0	794	0	2770
	Exports	833	351	0	113	0	1297
	TOTALS	2079	1523	5	963	152	4722
Jensen, DPL Level #3[c]	Muni. & Ind.	164	486	5	306	152	1113
	Irrig.	1086	990	0	794	0	2870
	Exports	964	609	0	113	0	1686
	TOTALS	2214	2085	5	1213	152	5669
Energy Industry Water Use[e] (This report)	L	62	260	4.5	41	33	400
	M	120	530	24	120	110	910
	H	130	720	35	430	270	1600

[a] Reservoir evaporation not included

[b] 1 acre-ft/yr = $1.23 \times 10^3 m^3$/yr

[c] From Reference 17 based on U.S. Bureau of Reclamation and U.S. Geological Survey data. DPL = Depletion = Diversion - Return.

[d] Side inflow above Lake Powell. Includes water salvage in Lake Powell area.

[e] Associated urban use is not included.

are: municipal and industrial (Muni. & Ind.), which includes energy industries; agricultural irrigation (Irrig.); and exports out of the basin, primarily to surrounding large metropolitan areas. Also shown in Table 3.2 are the average natural flows, historic uses, and the water uses for energy industries derived in this study. None of the depletion scenarios in Jensen's work exactly match those derived in this paper. The breakdown by tributary, however, does help to point out areas of greater potential conflict between energy developers and other water users. Also, the relative reliability of reservoir discharge, found by Jensen for his three total depletion levels, should still be of value, although the absolute values would probably be somewhat different for a somewhat different distribution of depletions among the tributaries.

The reliability of reservoir discharge as a function of total UCRB depletion level, as determined by Jensen (Reference 17), is shown in Table 3.3. Reliability is given in terms of shortfall or failure rates (the fractional number of years reservoirs fail to meet their full target discharges, given as a percent of total years the simulation was run). This does not mean that there is no discharge during reservoir shortfall or failure, but that the discharge is below the target value. For the same target discharges, the failure rates of the ten-year running averages of discharge behave similarly to those of the yearly discharges, but are about twice as high. The conclusion is that at a total-upper basin depletion level of 3.9 million acre-ft/yr (4.8 x $10^9 m^3$/yr) there is a very low probability of reservoir failure, at 4.7

TABLE 3.3

Predicted Reservoir Shortfall Rates as Functions of Total Upper Basin Depletions[a]

TOTAL UPPER BASIN DEPLETIONS (10^6 acre-ft/yr)	PERCENT OF YEARS RESERVOIRS FAIL TO MEET TARGET DISCHARGES	
	LAKE POWELL (target discharge = 8.23×10^6 acre-ft/yr)	LAKE MEAD (target discharge = 8.25×10^6 acre-ft/yr)
3.9	0.0	0.0
4.7	4.5	0.0
5.7	20.0	18.0

[a]Depletion = diversion - return. Data from Reference 17 for one synthetic streamflow trace (see text).

million acre-ft/yr ($5.8 \times 10^9 m^3$/yr) there is a good chance Lake Powell will fail at least a small fraction of the years, but only a low probability that Lake Mead will fail; at 5.7 million acre-ft/yr ($7.0 \times 10^9 m^3$/yr) there is a good chance both reservoirs will fail an appreciable fraction of the years.

Using these results, the aggregate water supply-reliability implications of the energy-development scenarios discussed previously can now be considered. To do this, it is convenient to refer back to Figure 3.1. Along with the average water-availability limit, the figure also displays the three depletion levels discussed by Jensen and their associated reservoir shortfall or failure probabilities (percent of years reservoirs fail to release their full target discharges: 8.23 million acre-ft/yr ($1.012 \times 10^{10} m^3$/yr) for Powell and 8.25 million acre-ft/yr ($1.015 \times 10^{10} m^3$/yr) for Mead.)

Considering the 7.3 quad/yr (7.7×10^{18} J/yr) level of development analyzed in the present study, under average flow considerations an increase over current consumption of up to 0.8 million acre-ft/yr ($9.8 \times 10^8 m^3$/yr) could be allowed for non-energy related activities in the UCRB (such as irrigation and export) before exceeding the maximum allowable annual consumption of 4.8 million acre-ft ($5.9 \times 10^9 m^3$). Unfortunately, by the 4.8 million acre-ft/yr ($5.9 \times 10^9 m^3$/yr) level there probably would already be reliability problems. Although there is only a small chance of Mead failure (and causing actual harm to the lower basin), there is a significant probability of Powell failure (and missing Compact obligations). Reservoir shortfall probabilities for other levels of energy production combined with other levels of increases in non-energy related UCRB uses can be read from Figure 3.1.

The situation for the Water Resources Council projection (4.92 million acre-ft/yr ($6.05 \times 10^9 m^3$/yr) total depletions) is similar to the 7.3 quad/yr case (7.7×10^{18} J/yr) although a little worse. This is because the chance of Mead failure would probably be increased over its previous low level. In References 51 and 23 no mention is made of reservoir shortfall, although reliability of flow is considered. At both the 15.2 million acre-ft/yr ($1.87 \times 10^{10} m^3$/yr) level of average virgin river flow and a reduced level of 13.8 million acre-ft/yr ($1.70 \times 10^{10} m^3$/yr) their most dire prediction is that the frequency of surplus discharges from Lake Powell over the 8.23 million acre-ft/yr ($1.012 \times 10^{10} m^3$/yr) target discharge would decrease. Their model deals only with the transition period during which depletions are increasing and surplus stored water is being used up.

For the EXXON projection, even without any increases for other than synfuel activities (not even coal-electric generation), there probably would be reliability problems. With increased water consumption for other activities over current levels, the reliability problems could be severe, i.e., both Powell and Mead failing a large fraction of the years. Recognizing that there would be problems, the EXXON report recommends that importation of water from other basins be considered.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The primary conclusion reached in this report is that the development of a large-scale energy recovery and conversion industry in the Upper Colorado River Basin (UCRB) would not be prevented by existing obligations to supply Colorado River water to downstream users in the Lower Colorado River Basin and Mexico. This conclusion does not presume importation of water into the upper basin and is true even when the reliability of supply is considered. In reaching this conclusion, however, water supply has been considered only on an aggregate basis for flows leaving the upper basin. Local water supply problems within the UCRB, such as a large, concentrated water demand on the White River for oil shale development, have not been considered. Water quality and other forms of environmental or societal impact also have not been considered.

The conclusion is based on an analysis which is considered to be conservative in the sense of overpredicting water demand for a given level of energy resource development and underpredicting supply. This is true for several reasons:

(1) The high end of realistic unit-water-requirement values for the energy industries have been used. Substitution of partial air cooling for wet cooling and use of low quality ground water instead of high quality surface water have not been considered.

(2) The 40-year period of record used to determine availability is for a relatively low flow period.

(3) The stochastic hydrologic model used to indicate the reliability of discharge from Lakes Powell and Mead predicts only the long term, steady-state situation, thus ignoring stored water available during the transition period to steady state.

The unit water requirements used in this analysis are shown below in Table 4.1. As explained in Chapter 2, they are considered conservative "best guess" estimates for fully integrated industries to be established in the UCRB as part of large-scale, commercial development.

TABLE 4.1

Unit Water Requirements of Energy Industries, Conservative "Best Guess" Estimates [Associated Urban Use Not Included]

INDUSTRY	UNITS: acre-ft/10^{12} Btu	$m^3/10^{12}$ J
Coal-Electric Generation	470	550
Coal-Slurry Pipeline	43	50
Coal Gasification (SNG)	91	110
Oil-Shale Processing	95	110

Based on these unit water requirements approximately 7 quad/yr (7.4×10^{18} J/yr) could be produced by water-intensive energy industries in the UCRB at a total water consumption cost of approximately

1 million acre-ft/yr ($1.2 \times 10^9 m^3$/yr). The composition of the energy industry which was used in this estimate is shown in Table 4.2. It includes tripling the present coal-electric generation capacity and producing approximately 3 million barrels per day oil equivalent ($4.8 \times 10^5 m^3$/d) from other coal processes and oil-shale development. By way of comparison, recent peak rates of liquid fuel imports were on the order of 8 million barrels per day. The 1 million acre-ft/yr water consumption includes both direct water consumption as shown in Table 4.2 and also a 10% increment for associated urban use.

TABLE 4.2

Energy Industry Composition and Direct Water Consumption
[For Entire Upper Colorado River Basin at One Level of Total Output]

INDUSTRY	CAPACITY	ANNUAL OUTPUT* (10^{12}Btu/yr)	PERCENT OF TOTAL OUTPUT**	WATER CONSUMPTION CONSERVATIVE "BEST GUESS" (10^3 acre-ft/yr)***
Coal-Electric Generation	3.03×10^4MW(e)	630	9	300
Coal-Slurry Pipeline	2.04×10^7t/yr	340	4	15
Coal Gasification (SNG)	3.4×10^9scfd	1200	17	110
Oil-Shale Processing	2.44×10^6bpd	5200	70	490
Total**		7300	100	910

*Annual load factors of 70% for coal-electric generation and 100% for all other processes were assumed. (1 Btu/yr = 1.055×10^3 J/yr).
**Inconsistancies are due to rounding.
***(1 acre-ft/yr = 1.23×10^3 m^3/yr).

On a long-term average basis, the use of 1 million acre-ft/yr (1.2 x $10^9 m^3$/yr) for energy development would leave about 0.8 million acre-ft/yr (9.8 x $10^8 m^3$/yr) for expansion of other water uses in the UCRB over present levels. This is an increase of more than 25%. As explained in Chapter 3, this is based on a conservative estimate of 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) being available to the upper basin on an average basis.

Unfortunately, long term average numbers do not determine the year-to-year reliability of the water supply. Flows in the tributaries of the Colorado River are extremely variable with time. The two very large reservoirs on the river, Lakes Powell and Mead, downstream of the major upper basin tributaries but upstream of almost all lower basin demand, help a great deal in regularizing the flow of water to downstream users. It is possible, however, that a sequence of drought years could cause a shortfall from one or both of these large reservoirs.

Reliability of downstream supply has been considered by means of a steady-state stochastic hydrologic model which is described in Chapter 3. Results of the model indicate that the use of 4.8 million acre-ft/yr (5.9 x $10^9 m^3$/yr) in the upper basin would probably mean small, but not necessarily insignificant problems in the reliability of flow to the lower basin. Lake Powell could fail to provide its <u>full</u> target discharge of 8.23 million acre-ft/yr (1.012 x $10^{10} m^3$/yr) a small fraction of the years (on the order of 5%); and even Lake Mead, the more downstream reservoir, might fail to provide its full target discharge of 8.25 million acre-ft/yr (1.015 x $10^{10} m^3$/yr), though for fewer years than would be the case with Lake Powell. At lower levels of total upper basin water consumption, the chances of reservoir shortfalls would be reduced. At a 3.9 million acre-ft/yr (4.8 x $10^9 m^3$/yr) level of total UCRB consumption, chances of shortfalls would be reduced nearly to zero. This is shown in Figure 3.1 in Chapter 3. Also shown in Figure 3.1 is the effect on UCRB water consumption of reducing energy production from the 7 quad/yr (7.4 x 10^{18} J/yr) level. For the same industry composition, if the projected level of energy production is halved, so is the projected energy-related water consumption. The 7 quad/yr (7.4 x 10^{18} J/yr) energy production level could be significantly reduced and still represent a large energy industry.

The primary conclusion is that aggregate downstream water-supply commitments do not stand in the way of large-scale energy development in the Upper Colorado River Basin. However, according to the conservative analysis leading to this conclusion there may be a few years in which total downstream supply obligations cannot be met (under conditions of a 7 quad/yr (7.4 x 10^{18} J/yr) level of energy production coupled with an increase in present water uses of over 25%). Thus, the issue of aggregate-supply reliability should not be completely ignored.

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